Laser power beaming for defense and security applications

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ABSTRACT

Laser power beaming – transmitting electric power without wires via laser – has been demonstrated for kilowatt power levels and kilometer distances. This paper reviews the demonstrated and projected capabilities and limitations of laser power beaming, and analyzes the requirements for several application areas relevant to defense and security: unmanned aerial vehicles (UAVs), communications relays, sensor networks, and field unit or forward base power.
Keywords: laser, power beaming, UAV, wireless power

1. INTRODUCTION

1.1 How Laser Power Beaming Works

Laser power beaming (LPB) uses electricity from a common source, such as the electrical grid or a portable generator, and converts it into light via a laser. This laser beam is then shaped with a set of optics, and directed via a gimbaled mirror (also known as the beam director) to a remote photovoltaic receiver. The PV receiver converts the light back into electricity to be used to charge a battery, run a motor, or do other work. Figure 1 below schematically shows the flow of power from input to output. In many ways, the system can be viewed as a kind of extension cord, with electrical power going in at one end, and electrical power coming out at the other end.

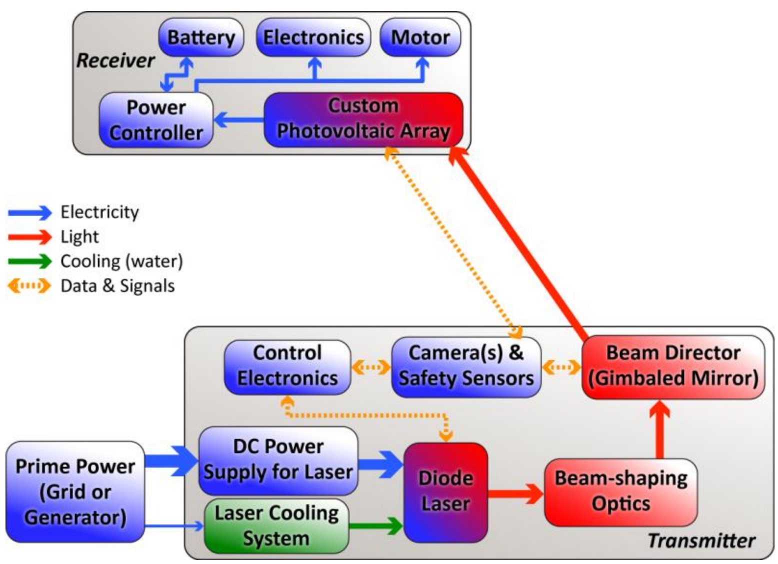

Figure 1. Schematic diagram of a laser power beaming system, showing the flow and conversion of power through the system.

1.2 History of Laser Power Beaming

The concept behind laser power beaming is not new. In fact, rudimentary tests demonstrating the transmission of electrical energy without wires were conducted approximately 100 years ago by Nikola Tesla [1], a Serbian scientist whose patents and theoretical work form the basis of the modern alternating current electrical systems and the modern AC motor.

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However, the first person to integrate all the elements of power beaming into workable system was William C. Brown, one of the pioneers of microwave energy for wireless power transmission. Brown published the first paper on the topic in 1961 and in 1964 demonstrated the technology with a model helicopter powered by wireless microwave beam [2].

In the ensuing years and as technology developed, the concept has been looked at frequently, with both microwaves and lasers proposed as the energy transmitters. In the 1980s, researchers began looking at the technology both for space-to-space energy transmission as well as for space propulsion. In the 1980s, a multinational group of researchers conducted tests using microwaves to power model aircraft, although the energy loss as the beam spread over long distances would be impractical for large applications.

While researchers continued various experiments using laser power beaming, such as demonstrating the feasibility of the technology for powering unmanned aircraft, until recently the power and cost of laser diodes – necessary for power beaming – have been a key barrier to the practical application of the technology. However, with recent advances in technology, laser diodes are becoming powerful, efficient, and inexpensive enough to make the commercial development of the technology feasible. In fact, in 2007, the Pentagon released a study recommending the development of space-based power systems using laser power beaming as one option for transmission. In the study, the Pentagon found that if placed correctly space power systems could provide enough solar energy in a single year equal to all known oil reserves on Earth, provide power for global U.S. military operations and deliver energy to disaster areas and developing nations.

Several small-scale demonstrations of laser power beaming have been done [3][*] but only within the last year have there been serious efforts to build complete laser power beaming systems, specifically to meet the requirements of the NASA Centennial Challenge for Power Beaming [4]. Our team, LaserMotive, was the only entrant to meet the minimum requirements, and in fact doubled the performance requirements for the Level 1 prize in 2009.

1.3 Performance & Limitations

Both specific power (W/kg) and energy density (J/kg) are critical for many remote power applications, UAVs in particular. For a given power draw, greater specific power allows for more payload weight on a UAV. Similarly, higher energy density implies longer endurance, which is one of the biggest requests by users of UAVs. Figure 2 below shows an approximate comparison of specific power and energy density for batteries, combustion engines, solar electric systems, and laser power receivers. Laser power systems effectively leave the energy source on the ground, where power is easier and cheaper to generate.

LaserMotive has demonstrated power beaming systems with a receiver specific power as high as 800 W/kg. By comparison, lithium-ion batteries used in small UAVs are generally used with a specific power in the range of 200-500 W/kg[2].

Solar electric systems do not technically have an infinite energy density because batteries have a limited lifetime, so the endurance of a solar electric based system will depend on the number of charge/discharge cycles (daily, or more frequent, for sunlight-based systems) that the battery can support. In contrast, laser power does not need to turn off at night, and can power the receiver continuously, with a battery only required during beam interruptions. Batteries or other energy storage are required at the receiver to handle beam interruptions.

With current laser cells, the deliverable power is limited mainly by cell cooling, and can easily exceed 6 kW/m^2, or about 1 HP per square foot.

Range is also an important consideration, and is limited primarily by source irradiance (W/m^2 sr) and source aperture size. Atmospheric scattering and absorption can degrade performance, but for many applications the beam has a strong vertical component or is at a reasonable altitude above ground level, either of which reduces atmospheric problems. Current diode laser technology and reasonable apertures can produce useful beam intensity at the receiver out to a range of ~10km. Longer distances can be achieved by switching to higher-quality sources (such as fiber lasers), although there is a penalty in cost and efficiency.

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[*] The earliest true laser power beaming demonstration we are aware of was done by one of the authors (Kare) in 1996, using an 808 nm laser diode array. Range (~10 m) and efficiency were low, but enough power was transmitted (3 watts) to run a small motor.

[2] These batteries can often be run at a higher power draw for a brief period of time, which would boost their measured specific power. In practice, though, they are run at a level which optimizes weight, energy density, and lifetime.

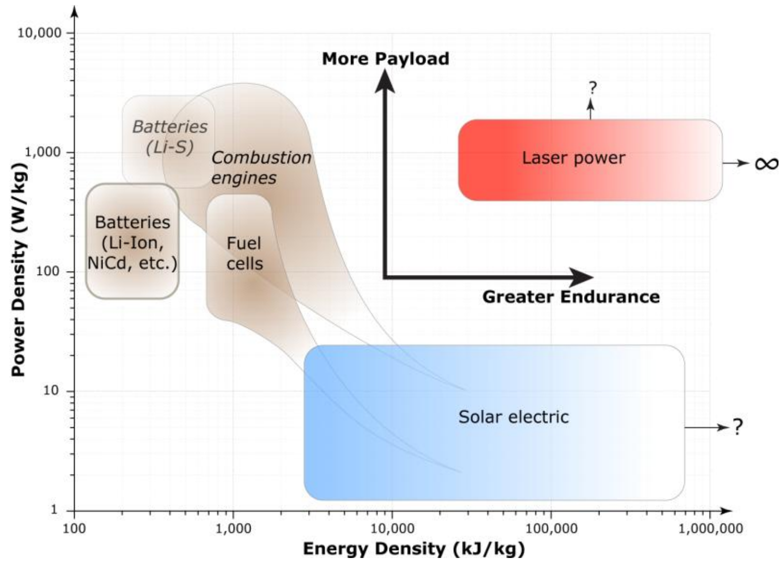

Figure 2. Comparison of specific power and energy density for various power sources.

The biggest limitation of laser power beaming is that it requires a line of sight (either direct or reflected off mirrors) between the transmitter and receiver. Light weather can reduce efficiency and range, but heavy weather (heavy rain or snow, or fog) can block transmission altogether.

Overall system efficiency (DC power in through to DC power out) can be more than 25%, although in practice it is currently closer to 20%. Off the shelf diode lasers currently exhibit up to ~60% DC-to-light efficiency, and the DARPA SHEDS program demonstrated [http://www.nlight.net/nlight-files/file/technical_papers/SPRCS05_stanford.pdf] up to 85% efficiency. Current photovoltaics can achieve more than 50% light-to-DC efficiency, and monochromatic conversion efficiencies can theoretically go higher. We expect overall system efficiency to exceed 30% within five years.

2. APPLICATIONS

2.1 Unmanned Aerial Vehicles (UAVs)

Unmanned aerial vehicles are seeing widespread military usage, and are growing in civilian applications as well. Many of the situations in which UAVs are used can benefit greatly from greater endurance. Example concepts of operations using UAVs will be discussed in section 3 below.

The actual UAV platform can be of almost any type, including conventional winged aircraft, helicopter-type platforms, or LTA vehicles, subject only to the need for a reasonable downward- or side-facing surface for the laser receiver. Smaller systems could use lightly-modified versions of existing battery-powered UAV designs, with fractional-HP to ~20 HP (15 kW) motors; in many cases, existing airframes can be retrofitted with laser receivers (and smaller batteries). Larger UAV classes, currently fuel-powered, would need more substantial modifications or new designs, but there is no obvious obstacle to supplying up to several hundred kW to a suitable airframe.

Laser power links enable two types of operation. One is near-continual powering of the UAV, which would therefore need only a very small energy storage device on-board. The other is intermittent recharging when the UAV returns to a designated area within view of the transmitter base station; in this case the UAV would need larger on-board energy storage. In both cases, the laser power link provides the many benefits discussed in section 1.3 above.

2.2 Remote Sensors and Communication Towers

Remote sensors are used for perimeter monitoring in military bases, gas and oil installations, and other large facilities, but it can be expensive to run power lines to the distant borders. It can be harder to justify this expense when an installation may be temporary, even if "temporary" means a few years.

Using laser power beaming, multiple remote devices, such as perimeter sensors or communications relays, receive power – from a few watts to several kW, continuously or on demand – via a set of fixed laser power links from a base station. The power links can also optionally provide secure control and high-bandwidth data return in all but the most extreme weather conditions.

Communication towers are often located in remote locations, far from regular power lines. Environmental restrictions can prohibit running power lines to a desired communication tower site, for example through forests or up a mountain.

Laser power can be installed for lower up-front capital cost. Once temporary installations are closed down, the laser power hardware can be relocated to a new site, enabling its capital cost to be shared among multiple projects.

2.3 Field Personnel

Soldiers often need to carry large quantities of batteries when they expect to be in the field for many days. This burden could be drastically reduced by having an aerial transmitter beam power down to the field units occasionally, as shown in Figure 3 below.

A small unit, such as a spotter team, receives power from a mobile source at defined times (for example, when the ground personnel are resting) which is used to recharge batteries. Multiple expendable receivers or relays can be placed a modest distance from the team, making the receivers harder for an enemy to target, and protecting the users if the receivers are attacked.

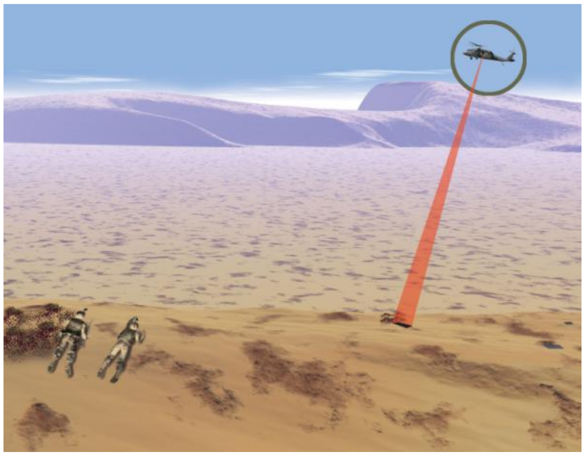

Figure 3. Example of field personnel using laser power beaming from an aerial source to recharge batteries.

2.4 Forward Operating Bases

Forward operating bases (FOBs), especially in the most remote regions, pose challenges for delivering power. Currently, fuel is trucked in, often at exorbitant cost in both money and lives. The fully-burdened cost of fuel at FOBs can range from $10/gal to more than $400/gal in extreme cases. And as of 2009?, more than 1,000 people had died delivering fuel to FOBs in Iraq and Afghanistan [5].

Laser power beaming can transmit, for example, 100kW or more to a small base or outpost from a prime power site – a larger base, or, e.g., a generator site at a roadhead or in a protected area. In this way, power is generated where it is cheaper and safer, and eliminates the logistical burden of numerous daily fuel truck runs through dangerous terrain.

In some cases, LPB could supplement a solar thermal installation. For example, the solar thermal hardware could use sunlight during the day (if there are no clouds), and the rest of the time it could point towards a remote laser transmitter. Such a dual-source solar thermal system would provide more flexibility in power sources.

3. UAV CONCEPTS OF OPERATIONS

LPB can be applied not only to many different current UAV missions, but it can enable new ways of operating as well.

3.1 Unlimited Patrol & Convoy Protection

A UAV can be continuously powered at long horizontal ranges, assuming it remains within line of sight of a beaming station. For a ground-based transmitter, a UAV would typically need to stay at least a few degrees above the horizon (see Figure 4 below). The beaming station could be mobile, which would allow the UAV to operate miles ahead of the path of a fleet of vehicles, providing advance surveillance and other functions for the mobile group.

For even longer ranges, as well as operation past hills or other obstacles, either the transmitter itself, or a relay mirror, could be mounted on an airborne platform – an airplane, aerostat, or UAV.

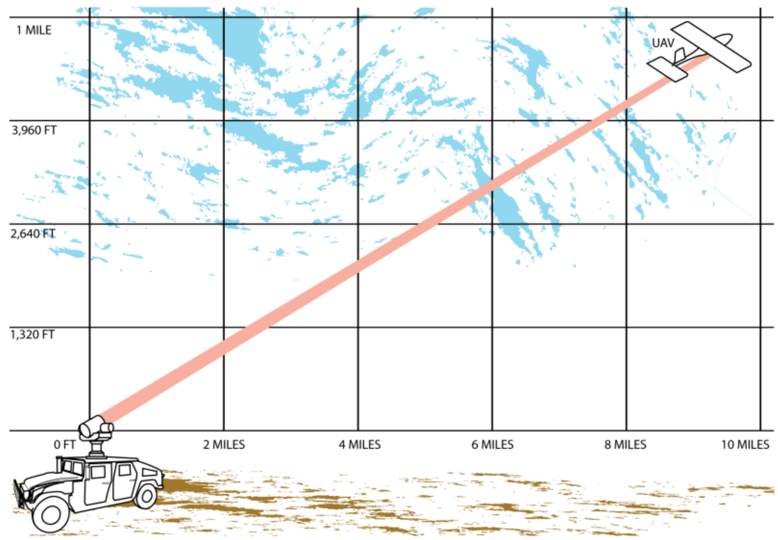

Figure 4. Beaming from a mobile transmitter for convoy protection.

One specific implementation would be to have a helicopter travel with a convoy, nominally flying slightly ahead of the convoy to provide surveillance while being continually powered by laser from one of the vehicles in the convoy. When a suspicious site is seen, the laser could be turned off and the helicopter could fly down (operating on batteries) closer to the ground for a close-up inspection of a possible IED site, or to look in a culvert, or under a bridge.

3.2 Stationary Observing and Communications Platform (Permanent Geostationary Atmospheric Satellite)

Situational awareness can be vastly improved through elevated observing platforms, and UAVs are well-suited to providing high-altitude surveillance. Downtime due to the need for refueling reduces coverage and adds logistical loads to personnel. Every landing brings with it a risk of damaging the UAV. Power beaming to electric UAVs would enable 'eternal' UAVs which could operate 24/7, providing continuous surveillance without the risks and personnel requirements of repetitive take-offs, landings, and refuelings.

The UAVs could operate at any practical altitude, from 100 meters (or lower) to over 25 kilometers (for airships) under constant laser power. Military bases would find micro-UAVs, such as quadrocopters, of use for base patrol, or more traditional airplane UAVs for higher-altitude area observations. Naval vessels would deploy an airplane UAV or perhaps an aerostat or similar lighter-than-air (LTA) ship for extreme long-distance observations and communications. See Figure 5 below for examples.

A permanently-stationed, high-altitude UAV would behave, in many ways, like a low-cost high-performance geostationary satellite, except that it would be located only a few miles above ground. Such an eternal UAV would be able to provide surveillance and communications across a region continuously.

There are also ways to provide a rapidly deployable rotary wing craft to an altitude of ~100m to provide a communications relay platform as well as surveillance capability. The entire system (aerial platform and transmitter) for this smaller application could be very compact – the size of a footlocker, for example.

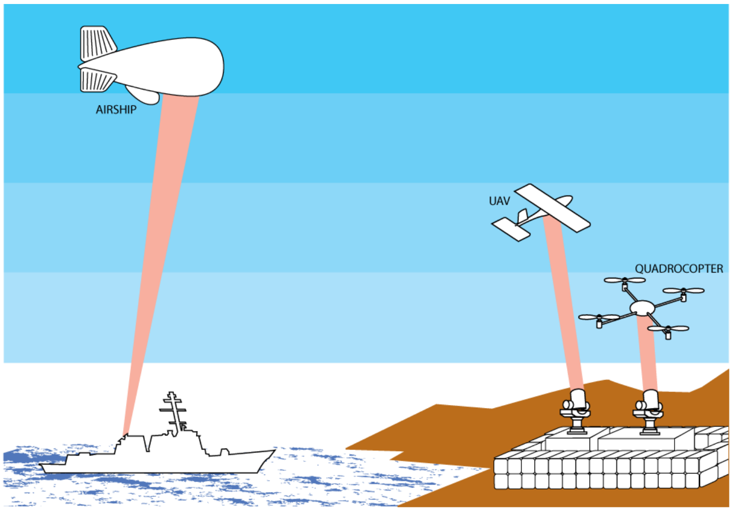

Figure 5. Atmospheric satellites.

3.3 Multi-ISR

Beam-powered UAVs can also operate far away from the beaming station through use of on-board energy storage (e.g., batteries). UAVs can remain airborne indefinitely by regularly returning to the area near a beaming station to recharge its batteries. In the example shown in Figure 6, a mobile beaming station serves as the "refueling" point for an observation UAV which loiters over the beaming station until its on-board storage is full, then it flies to its target (which could be 100 miles or more away). It loiters over the target, sending back imagery and sensor data, until its power level is low enough that it needs to return to the beaming station to recharge.

The beaming station does not have to be at the same location that the UAV is launched from, and in fact there can be many beaming stations strategically located along a path of interest for the UAV, to vastly extend its range and/or to enable it to alternate between targets.

There does not need to be a one-to-one ratio between beaming stations and UAVs. One beaming station support multiple UAVs which rotate in and out of recharging mode. A network of beaming stations can support a large number of UAVs with flexible flight paths.

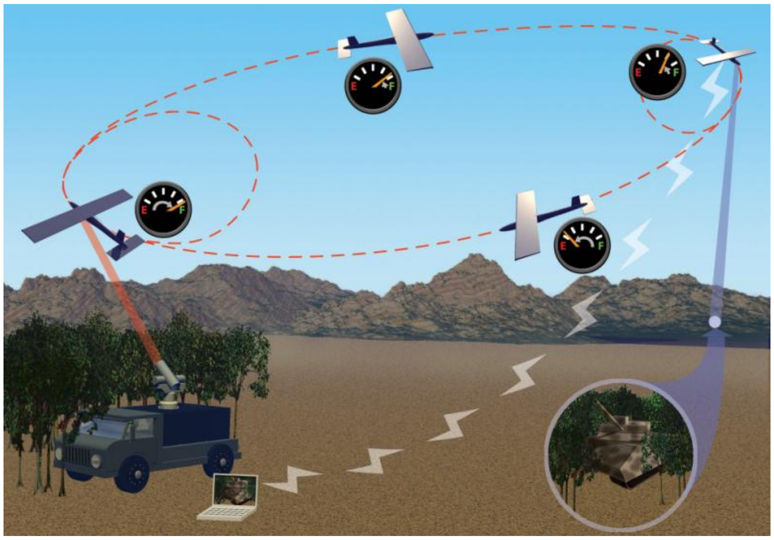

Figure 6. Recharge and fly out of sight.

Another example of recharging for extended missions is relatively small UAVs flying within a few kilometers of a base, e.g., for perimeter patrol. Many UAVs could be rotated between recharging near a beaming station and out to near-base missions.

Because in-flight recharging can be done at relatively short range, optics requirements are modest, and the impact of clouds and other beam obstacles is reduced. However, both transmitter and receiver must handle much more than the mission-average power.

4. DEMONSTRATIONS

4.1 NASA Power Beaming Challenge

Part of the NASA Centennial Challenges program, the Power Beaming Challenge aimed to spur development of power beaming technologies that would be applicable to near-term NASA programs, such as powering satellites or planetary rovers.. LaserMotive won the Power Beaming Challenge Level 1 prize in 2009.

To win, LaserMotive demonstrated a complete power beaming system that was used to power a robotic climber to a height of one kilometer. It was the only entrant to develop its own laser system, which was built around infrared laser diode arrays supplied by DILAS Laser Diodes Inc.

The records LaserMotive set in the 2009 Challenge include:

- Greatest distance for laser power beaming: 1 km (3280 ft., 0.62 miles)
- Most power transferred to a receiver: over 1 kW
- Highest efficiency power beaming: over 10%, DC power to DC power
- Fastest climbing speed up a cable at this competition: 3.97 m/s (8.88 miles per hour)
- Specific power in a laser receiver of ~500 W/kg

4.2 Quadrocopter UAS

In 2010, LaserMotive partnered with German robotic helicopter manufacturer Ascending Technologies to demonstrate laser powered flight of a UAV. The flight [6] was the longest laser powered flight on record at 12 hours, 26 minutes and 56.9 seconds, which represents a duration of 150 times the battery lifetime. The flight set the following records:

- Longest hovering flight duration for an untethered electric vehicle: Limited only by the venue; the Ascending Technologies Pelican quadrocopter and the LaserMotive power system were both capable of continuing indefinitely.
- Endurance record for any VTOL aircraft in this weight class
- Longest beamed-energy-powered flight of any type

In addition, the flight marked the following key milestones towards operational laser-powered UAVs:

- Repeated fully automatic acquisition of UAV by laser tracking system
- In-flight battery recharging
- Automatic position hold in beam, with the laser tracking system controlling the UAV position
- "Class I" operation, meeting US and international laser exposure limits everywhere on the ground.

5. CONCLUSION

Laser power beaming is a fundamentally new method of delivering energy. It acts as a "wireless extension cord" to deliver power to end-users where it might otherwise be too expensive or impractical to run normal power lines. Defense and security-related applications include a variety of mission scenarios for unmanned aerial vehicles, as well as remote sensors, communication towers, field personnel and forward operating bases. The component technologies have advanced to the point where full systems have been demonstrated in the field and are economical for the above-mentioned applications.

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